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16. ABSTRACT

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JOURNAL ARTICLE

A STUDY OF TURBULENT ENERGY OVER COMPLEX TERRAIN (STATE, 1978)

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Abstract. The complex structure of the earth's surface influenced atmospheric parameters pertinent to modeling the diffusion process during the 1978 'STATE' field study. The Information Theory approach of statistics proved useful for analyzing the complex structures observed in the radiometric surface temperature signals as measured from an aircraft. Results show that regardless of their complexities, these temperature processes are well approximated as Gaussian processes. Turbulent kinetic energy is shown to increase as the surface temperature signals become more complex. The nature of these variations is examined for five different categories of agricultural land as defined by percent cultivation and percent forestation.

1. Introduction

A concerted effort to study Sulfur Transport and Transformation (STATE) as emitted from a Tennessee Valley Authority (TVA) coal-burning electrical generating plant on the Cumberland River near Clarksville, Tennessee, was sponsored by the Environmental Protection Agency (EPA) during the month of August 1978 (Schiermeier *et al.*, 1979). Although there were many aspects of the study, this paper is concerned only with the airborne measurements of atmospheric turbulence parameters and their variability with emphasis upon the infrared temperature characteristics of the underlying terrain.

2. Terrain

The experimental area was confined to north central Tennessee and western Kentucky. It is bounded on the north by the Ohio River, on the west by the dammed portions of the Cumberland and Tennessee Rivers (Land between the Lakes Recreation area), and on the east by Nashville, Tennessee. The northern one-third of the region consists of forested hills with large wide agricultural valleys, while the central portions are represented by cleared flat farmlands with small woodlots. The southern and western portions are composed of the forested Tennessee Ridge with rolling to high ridge crests and valley agriculture. Farms in these regions average 80 ha with acreage being used for small grain, soybeans, corn, red clover, tobacco, and pasture (Soil Survey, Montgomery County, Tennessee, 1975). Elevation over the area can vary from the river and creek valleys (108 to 138 m mean sea level, MSL), to flat or rolling upland plains (150 m MSL), to ridge tops at 210 m MSL. In general, relief ranges from 15 to 90 m. These topological and agricultural characteristics have been divided for this study into the five regions of Table I.

Boundary-Layer Meteorology **25** (1983) 17–23. 0006–8314/83/0251–0017$01.05.

TABLE I

Correlations of kinetic energy of turbulence as measured at flight level with the surface infrared temperature as well as temperature fluctuations at flight level.

Land-Use and Terrain		Correlation K.E. vs ln σ	Sample size
Forest: more than 80% forest cover over hills & valleys.	T(air)	0.56	24
	T(air)	0.76	
Elkton hills: Large forested hills and wide valleys with agriculture. 50% agri., 50% forest	T(ir)	0.56	34
	T(air)	0.63	
Dickson hills: A mixture of hills and valleys with random agriculture. 60% agri., 40% forest.	T(ir)	0.43	32
	T(air)	−0.16	
Elkton Plain: A large flat and fertile farming district with small woodlots. 85% agri., 15% forest.	T(ir)	0.81	46
	T(air)	0.09	
Madisonville: Large fields with a large forested swamp. 80% agri., 20% forest	T(ir)	0.74	11
	T(air)	0.16	

3. Measurements

The data considered here are airborne (gust-probe) measurements of the fluctuating wind components in the direction of mean wind u', as well as cross-wind and vertical fluctuations, v' and w', respectively. The primes denote departures from the mean. A small bead thermistor and microwave refractometer provided measurements of air temperature (T') and water vapor (ρ_v'), respectively. These measurements allow determination of the vertical transport via the eddy correlation method:

$$\begin{aligned} &\text{Evaporation} = \overline{\rho_v' w'} \\ &\text{Sensible Heat Flux} = \overline{T' w'} \\ &\text{Momentum} = \overline{u' w'}. \end{aligned} \tag{1}$$

The overbars in (1) reflect averages for observational runs of five to seven minutes flight time, at a sampling rate of 40 Hz. Again, the primes denote fluctuations about that mean (i.e., $\overline{u' w'} = \overline{(u - u')(w - w')}$). Surface (earth) radiative temperature was determined by a downward looking infrared radiometer (PRT 5). Thermal sensing was performed in the 8 to 14 μm region of the spectrum with an average field-of-view radius of 8.76 m at 500 m above ground level (agl). The data were collected at various heights from 100 to 1000 m above ground but below cloud base. Details of this system as used in previous major experiments are given elsewhere for the Carribean (Bean *et al.*, 1972), and over Lake Ontario (Bean *et al.*, 1975).

There were some two hundred observation runs made during the course of the experiment. Mean values were computed for each parameter on each run. The corresponding time series were then de-meaned and high-pass filtered. The filter's half power point (i.e., that frequency at which the amplitude has dropped to one-half) is 0.01 Hz. Since the aircraft was traveling at approximately 80 m s^{-1}, the half-power point corresponds to a wavelength of 8 km. This effectively restricts analysis to conditions of micro-land use, i.e., event scales smaller than 5 km but including the average size of rural land parcels. After filtering, variances and covariances were computed for the runs.

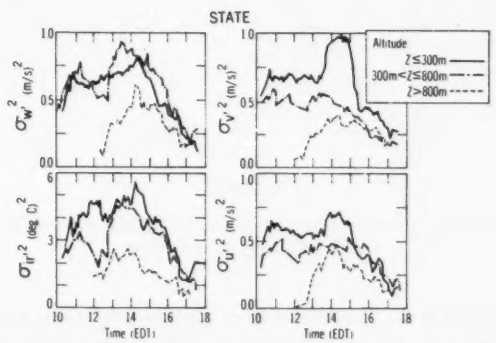

Fig. 1. Mean diurnal trends of turbulent intensities and variance of surface infrared temperature.

Figure 1 shows the average diurnal trend in the turbulent intensities ($\sigma_{w'}^2$, $\sigma_{v'}^2$, $\sigma_{u'}^2$), and the infrared surface temperature variance ($\sigma_{ir'}^2$). All of the variables show similar diurnal trends which increase around noon to 14:00 and decrease thereafter. The cross-wind component of turbulent intensity ($\sigma_{v'}^2$) has a pronounced peak between 13:00 and 14:00. We also note that measurements taken above 800 m agl tend, on the average, to be smaller than the average values observed at lower altitudes. In general, observations below 800 m agl are not significantly different. While the diurnal trend for the total turbulent intensity:

$$\text{K.E.} = \sigma_{w'}^2 + \sigma_{v'}^2 + \sigma_{u'}^2 \tag{2}$$

is well defined, the scatter about this trend is quite large. We now wish to account for this variability.

4. Consideration of IR Surface Temperature Fluctuations

Examination of the probability distributions derived from the time series for the IR surface temperature displayed a marked tendency towards a normal distribution. This observation was tested following Shannon and Weaver (1949) by evaluating the statistical entropy, H, as given by

$$H = -\sum_{i}^{n} p_i \ln p_i \tag{3}$$

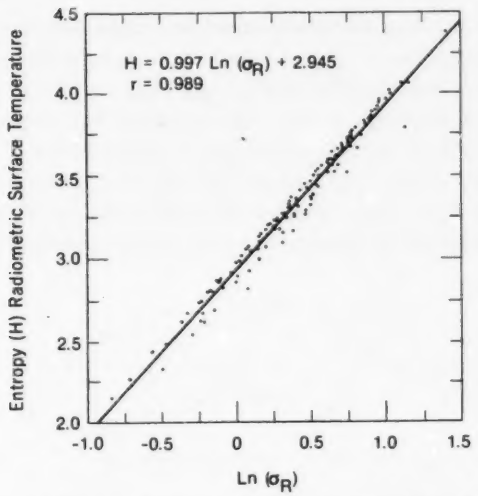

Fig. 2. Regression of radiometric surface entropy on the natural logarithm of the standard deviation of radiometric surface temperature.

where p_i is the probability of the occurrence of IR temperature in a given interval of the range of IR temperature. H was evaluated for each of the experimental samples from summation of (3) over 200 intervals between -18 to $+15$ °C. Maximum entropy is obtained by assuming a fixed standard deviation and a theoretical normal distribution to obtain, again following Shannon and Weaver (1946),

$$H = a \ln \sigma + b \tag{4}$$

i.e., one would expect that H is a linear function of the natural log of the standard deviation of surface temperature. The standard deviation was calculated for each of the available samples (202) and compared to H as calculated from (3). The results are given in Figure 2 where, indeed, H and ln σ are linearly related with a correlation coefficient of 0.989, strongly suggesting that the infrared temperature fluctuations are approximately normal or Gaussian distributed.

This conclusion is perhaps not surprising since many factors can influence the entropy of a radiometric temperature signal. The atmosphere between the sensor and the earth has a significant effect on the intensity and spectral composition of the energy being recorded by the radiometer. However, atmospheric conditions below 800 m agl were generally well mixed during the periods of observation. As a result, atmospheric absorption, scatter, and emission along the sensing path are effectively constant. The major effect is a biased mean temperature with only a minor contribution to the variance. Other factors, such as land utilization, vegetative cover, topography, cloud shadow distribution, sun angle, soil moisture content arising from rainfall distribution and history, as well as the emissivity of surface materials, are all major contributors to entropy generation.

5. Kinetic Energy Considerations

The question of the transmittal of the differential heating of the earth's surface into forced vertical convection is one of great complexity. The authors have chosen to ask instead how much information is contained in these measurements of differential heating as is related to turbulent mixing in the sub-cloud layer. The information theory definition of entropy was chosen because of its application to science (Brillouin, 1962), a host of classical problems in mathematics and statistical mechanics (Tribus and Levine, 1978), as well as probability mapping of many diverse properties studied in human geography (Haggett *et al.*, 1977). In general, the logarithmic law is chosen in order to ensure additivity of the information, or lack of it, contained in independent situations.

We assume that the transmittal of differential heating of the earth's surface into vertical convection is contained within the undefined energy (Brillouin calls it the negentropy) as expressed by the following equations for the kinetic energy (K.E.):

$$\text{K.E.} = \ln(\sigma_r) \tag{5}$$

where

$$\text{K.E.} = \sigma_{u'}^2 + \sigma_{v'}^2 + \sigma_{w'}^2 \tag{6}$$

the u', v', and w' being the down, cross, and vertical components of the wind. Restricting observations to below cloud base, equation (5) was tested for linear correlation. Results of this comparison are given in Figure 3 where a moderate but useful correlation of 0.64 is observed between $\ln(\sigma_r)$ and the kinetic energy. This analysis was extended by examining soil surveys and Land-Sat imagery to establish regions of

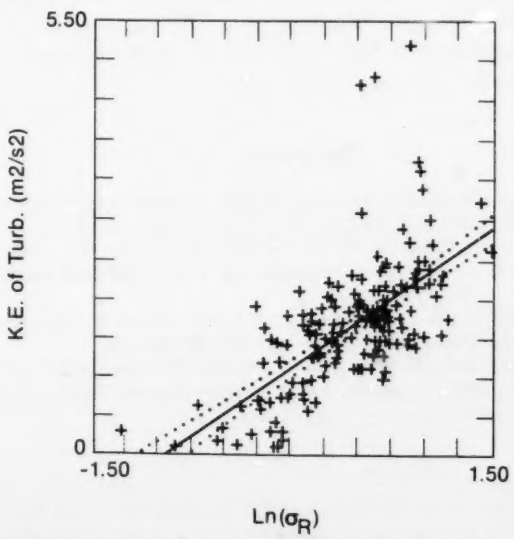

Fig. 3. Regression of kinetic energy of turbulence on the natural logarithm of the standard deviation of the radiometric surface temperature. The correlation coefficient is 0.64.

dissimilar land-use and vegetative cover. Five different areas could be clearly defined by percent forestation and percent cultivated farm lands. The entropy relation presented in Equation (5) was tested for variability between each category. Results given in Table I show that $\ln(\sigma_r)$ (entropy) of radiative surface temperature has a correlation of 0.81 with the turbulent kinetic energy over cultivated regions, decreasing to 0.42 over forested hills and valleys. This suggests that land usage characterized by heavy cultivation more directly contributes to turbulent energy.

The above arguments are general and apply equally well to fluctuations in air temperature at flight altitude. The relationship betwee H and $\ln(\sigma_a)$, σ_a being that of air temperature at flight altitude, was tested following the above procedures and yielded a correlation of 0.995. Testing for a linear relationship between $\ln(\sigma_a)$ and K.E. produced a moderate correlation of 0.63, about the same order of magnitude as observed with surface temperature. However, the correlation between σ_r and σ_a is 0.09 and when examined for correlation as categorized by land use, this correlation, also listed in Table I, shows much more erratic behavior than that with the surface IR temperature. We may conclude that the lack of correlation between σ_r and σ_a precludes the existence of organized thermals as the source of variation about the diurnal trend.

6. Conclusions

The complex character of surface infrared temperature variability is found to be systematically related to the kinetic energy intensity in the sub-cloud layer over a fairly wide range of underlying land utilization. This is a promising finding in that a similar relationship may be found with satellite data and thus allowing extension to other regions without expensive in-situ measurements. The same cannot be said of the fluctuations of air temperature at flight level. These preliminary conclusions must be checked for other seasons and geographical regions.*

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